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Academic discussion

Review of research in internal-wave and internal-tide deposits of China: Discussion

G. Shanmugam

Department of Earth and Environmental Sciences, The University of Texas at Arlington, Arlington, TX 76019, USA

Abstract This discussion of a review article by Gao *et al.* (2013), published in the *Journal of Palaeogeography* (2(1): 56–65), is aimed at illustrating that interpretations of ten ancient examples in China and one in the central Appalachians (USA) as deep-water deposits of internal waves and internal tides are unsustainable. This critical assessment is based on an in-depth evaluation of oceanographic and sedimentologic data on internal waves and internal tides derived from 332 print and online published works during 1838–January 2013, which include empirical data on the physical characteristics of modern internal waves and internal tides from 51 regions of the world′s oceans (Shanmugam, 2013a). In addition, core and outcrop descriptions of deep-water strata from 35 case studies worldwide carried out by the author during 1974–2011, and a selected number of case studies published by other researchers are evaluated for identifying the sedimentological challenges associated with distinguishing types of bottom-current reworked sands in the ancient sedimentary record. The emerging conclusion is that any interpretation of ancient strata as deposits of internal waves and internal tides is premature.

Key words baroclinic sands, contour currents, deep water, facies models, internal waves, internal tides, pycnoclines, shelf edge

1 Introduction

The topic of internal waves and internal tides is of considerable interest to both oceanographers and sedimentologists worldwide. In this context, the paper by Gao *et al.* (2013) entitled "Review of research in internal-wave and internal-tide deposits of China" is of significance not only for the Chinese readership but also for the international readership. However, their paper suffers from fundamental deficiencies. In pointing out these problems and in advancing the primary mission of the *Journal of Palaeogeography*, which is to promote the communication and cooperation between Chinese and international scholars, I avail this opportunity by offering basic information and explanation.

The article by Gao *et al.* (2013) is the first major review of research on ancient deposits. Therefore, a rigorous scrutiny of the review is imperative. Otherwise, the article will leave an indelible impression that the science of internal waves and internal tides is settled. From an oceanographic viewpoint, it is far from settled (Garrett and Kunze, 2007). From a sedimentological point of view, it is at a crisis stage (Shanmugam, 2008a, 2012a, 2012b, 2013a, 2013b, 2013c, 2013d, 2013e, 2014) in the Thomas Kuhn′s (1996) five stages of scientific revolutions: (1) random observations, (2) first paradigm, (3) crisis, (4) revolution, and (5) normal science.

1.1 Global data sets

Deep-water processes and facies models are full of conflicts (Shanmugam, 2012b). Eventually, all major conflicts

* Corresponding author. E-mail: shanshanmugam@aol.com.
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must be resolved. To this end, the subject of internal waves and internal tides has generated five published debates, including this one, since 2008 (Table 1). Although various sedimentological issues raised in these debates are critical here, Gao *et al.* (2013) have neglected to address them. In particular, a clear understanding of the origin of bottom-current reworked sands (BCRS), which include reworked sands by baroclinic currents (Shanmugam, 2013a), has direct implications for process sedimentology and petroleum geology. In this context, descriptions of deep-water strata from 35 case studies worldwide are considered (Figure 1, Table 1). These global data sets include 7832 meters of conventional cores from 123 wells, representing 32 petroleum fields. Finally, selected modern and ancient case studies of deep-water systems published by other researchers are discussed in illustrating the challenges in distinguishing baroclinic sands (see Section 9). Hopefully, this comprehensive discussion and related reply will motivate others to undertake future research.

1.2 Historical backgrounds

Gao *et al.* (2013) state that "*The study of internal waves has a long history in oceanography which can be traced back to the study of the interfacial wave theory by Stocks in* 1847 (*Munk*, 1981)." But Benjamin Franklin in 1762 was the first one who demonstrated that internal gravity waves on the interface between oil and water have a much longer period than do surface waves with the same wavelength (Phillips, 1974). Early observations of internal waves in nature have been attributed to Russell (1838) and even to earlier Viking times (Ekman, 1904). In the 20th century, the late Dr. John Ralph Apel is considered the "Father" of SEASAT (one of the earliest Earth-observing satellites by NASA) in the use of remote sensing for investigating the physics of internal waves and internal tides (Jackson, 2004).

2 Fundamental concepts

2.1 Baroclinic oceans

The concept of 'Barotropic vs. Baroclinic' is of paramount importance in understanding currents associated with internal waves and internal tides (CIMAS, 2012). This is because these concepts are directly related to developing sedimentological criteria for recognizing ancient deposits. In an oceanographic context, barotropic currents are driven by the slope of the water surface, and these currents are typical of the well-mixed shallower (shelf) part of the ocean (Figure 2). In contrast, baroclinic currents are

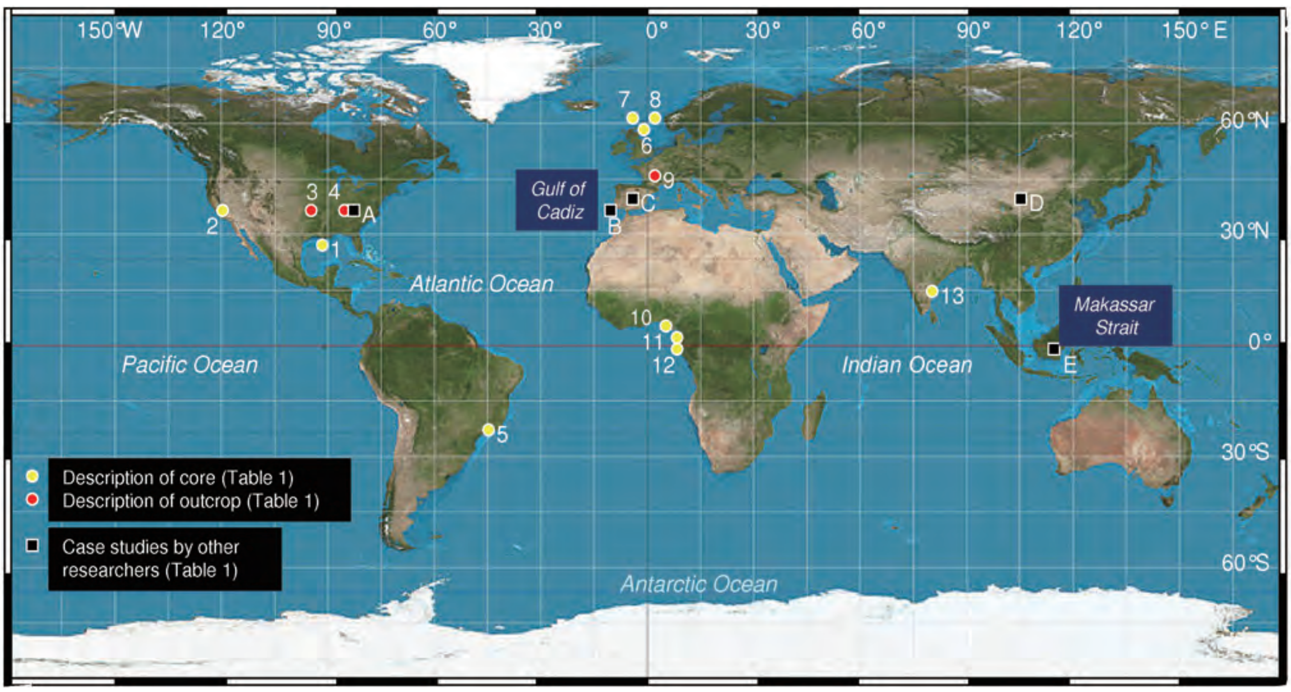

Figure 1 Map showing five case studies (A, B, C, D and E) by other researchers that include the outcrop study of internal-tide deposits in the central Appalachians by Gao and Eriksson (1991). Note locations of case studies of deep-water sandstones by the author. See Table 1 for details of core and outcrop descriptions. Blank world map credit: http://upload.wikimedia.org/wikipedia/commons/8/83/Equirectangular_projection_SW.jpg (accessed April 30, 2014).

Table 1 Part I: Case studies by other researchers that are used in this article (Locations: A, B, C, D and E, filled squares, see Figure 1). Part II: Case studies by the author based on conventional core and outcrop description worldwide (Locations: 1–13, filled circles, see Figure 1). Also note that traction structures of bottom-current origin, which may include baroclinic currents associated with internal waves and tides, are common in all 35 case studies listed.

Location symbol and number in Figure 1	Number of case studies	Thickness of core and outcrop described*	Comment (This paper)
Part I: Case studies by other researchers			
A. Southern Appalachians (Gao and Eriksson, 1991) (see Gao *et al.* 2013, their Figure 1 for locations of ten study sites in China)	Valley and Ridge, Virginia	Outcrop section	Discussion of problematic origin of bidirectional cross-bedding in internal-tide deposits (This article)
B. Gulf of Cadiz (Stow *et al.*, 2013)	Cadiz Channel	2 gravity cores and over 3000 submarine photographs (Stow *et al.*, 2013)	Discussion of distinguishing contourites from internal-wave and internal-tide deposits (This article)
C. NE Spain (Pomar *et al.*, 2012)	Ricla Section, Upper Jurassic	1 Outcrop section (Bádenas *et al.*, 2012; Pomar *et al.*, 2012)	Discussion of problematic origin of hummocky cross-stratification in internal-wave and internal-tide deposits (Shanmugam, 2013a, 2013b)
D. China (He *et al.*, 2011)	Ningxia, Middle Ordovician	Several outcrop sections (He *et al.*, 2011)	Discussion of problematic internal-wave and internal-tide deposits in abyssal basin environments, without seafloor irregularities (Shanmugam, 2012a)
E. Makassar Strait (Saller *et al.*, 2006)	Kutei Basin, Miocene	2 wells? (Saller *et al.*, 2006, 2008a, 2008b)	Discussion of problematic interpretation of turbidites without modern analogs, and the alternative tidalite option (Shanmugam, 2008c)
E. Makassar Strait (Dunham and Saller, 2014)	Kutei Basin, Miocene	2 wells (Saller *et al.*, 2006, 2008a, 2008b)	Reply to a discussion on internal waves and tides documenting modern deep tidal currents (Shanmugam, 2014)
Part II: Case studies by the author			
1. Gulf of Mexico, U.S. (Shanmugam *et al.*, 1988)	1. Mississippi Fan, Quaternary, DSDP Leg 96	~ 500 m DSDP core (selected intervals described)	Modern submarine fan
1. Gulf of Mexico, U.S. (Shanmugam *et al.*, 1993a, 1993b; Shanmugam and Zimbrick, 1996)	2. Green Canyon, Late Pliocene, 3. Garden Banks, Middle Pleistocene 4. Ewing Bank 826, Pliocene−Pleistocene 5. South Marsh Island, Late Pliocene 6. South Timbalier, Middle Pleistocene 7. High Island, Late Pliocene 8. East Breaks, Late Pliocene−Holocene	1067 m Conventional core and piston core 25 wells	Sandy mass-transport deposits and bottom-current reworked sands common
2. California (Shanmugam and Clayton, 1989; Shanmugam, 2006a, 2012b)	9. Midway Sunset Field, Upper Miocene, onshore	650 m Conventional core 3 wells	Sandy mass-transport deposits and bottom-current reworked sands

Table 1, continued

Location symbol and number in Figure 1	Number of case studies	Thickness of core and outcrop described*	Comment (This paper)
3. Ouachita Mountains, Arkansas and Oklahoma, U.S. (Shanmugam and Moiola, 1995)	10. Jackfork Group, Pennsylvanian	369 m 2 outcrop sections	Sandy mass-transport deposits and bottom-current reworked sands common
4. Southern Appalachians, Tennessee, U.S. (Shanmugam, 1978; Shanmugam and Benedict, 1978)	11. Sevier Basin, Middle Ordovician	2152 m 5 outcrop sections	Ancient submarine fan
5. Brazil (Shanmugam, 2006a, 2012b)	12. Lagoa Parda Field, Lower Eocene, Espirito Santo Basin, onshore 13. Fazenda Alegre Field, Upper Cretaceous, Espirito Santo Basin, onshore 14. Cangoa Field, Upper Eocene, Espirito Santo Basin, offshore 15. Peroá Field, Lower Eocene to Upper Oligocene, Espirito Santo Basin, offshore 16. Marlim Field, Oligocene, Campos Basin, offshore 17. Marimba Field, Upper Cretaceous, Campos Basin, offshore 18. Roncador Field, Upper Cretaceous, Campos Basin, offshore	200 m Conventional core 10 wells	Sandy mass-transport deposits and bottom-current reworked sands common
6. North Sea (Shanmugam *et al.*, 1995)	19. Frigg Field, Lower Eocene, Norwegian North Sea 20. Harding Field (formerly Forth Field), Lower Eocene, U.K. North Sea 21. Alba Field, Eocene, U.K. North Sea 22. Fyne Field, Eocene, U.K. North Sea 23. Gannet Field, Paleocene, U.K. North Sea 24. Andrew Field, Paleocene, U.K. North Sea 25. Gryphon Field, upper Paleocene-lower Eocene, U.K. North Sea	3658 m Conventional core 50 wells	Sandy mass-transport deposits and bottom-current reworked sands common
7. U.K. Atlantic Margin (Shanmugam *et al.*, 1995)	26. Faeroe area, Paleocene, west of the Shetland Islands 27. Foinaven Field, Paleocene, West of the Shetland Islands	Thickness included in the N. Sea count 1 well Conventional core 1 well	Sandy mass-transport deposits and bottom-current reworked sands common
8. Norwegian Sea and vicinity (Shanmugam *et al.*, 1994)	28. Mid-Norway region, Cretaceous, Norwegian Sea 29. Agat region, Cretaceous, Norwegian North Sea	500 m Conventional core 14 wells	Sandy mass-transport deposits and bottom-current reworked sands common
9. French Maritime Alps, Southeastern France (Shanmugam, 2002, 2003)	30. Annot Sandstone, Eocene−Oligocene	610 m** 1 outcrop section (12 units described)	Sandy mass-transport deposits and bottom-current reworked sands common (deep tidal currents)

Table 1, continued

Location symbol and number in Figure 1	Number of case studies	Thickness of core and outcrop described*	Comment (This paper)
10. Nigeria (Shanmugam, 1997b ; Shanmugam, 2006a, 2012b)	31. Edop Field, Pliocene, offshore	875 m Conventional core 6 wells	Sandy mass-transport deposits and bottom-current reworked sands common (deep tidal currents)
11. Equatorial Guinea (Famakinwa *et al.*, 1996; ; Shanmugam, 2006a, 2012b)	32. Zafiro Field, Pliocene, offshore 33. Opalo Field, Pliocene, offshore	294 m Conventional core 2 wells	Sandy mass-transport deposits and bottom-current reworked sands common
12. Gabon (Shanmugam, 2006a, 2012b)	34. Melania Formation, Lower Cretaceous, offshore (includes four fields)	275 m Conventional core 8 wells	Sandy mass-transport deposits and bottom-current reworked sands common
13. Bay of Bengal, India (Shanmugam *et al.*, 2009)	35. Krishna-Godavari Basin, Pliocene	313 m Conventional core 3 wells	Sandy debrites and tidalites common
Total thickness of rocks described by the author		11,463 m	

* The rock description of 35 case studies of deep-water systems comprises 32 petroleum-producing massive sands worldwide. Description of core and outcrop was carried out at a scale of 1:20 to 1:50, totaling 11,463 m, during 1974−2011, by G. Shanmugam as a Ph.D. student (1974−1978), as an employee of Mobil Oil Corporation (1978−2000), and as a consultant (2000−2011). Global studies of cores and outcrops include a total of 7832 meters of conventional cores from 123 wells, representing 32 petroleum fields worldwide (Shanmugam, 2013c, 2013e).These modern and ancient deep-water systems include both marine and lacustrine settings.

** The Peira Cava outcrop section was originally described by Bouma (1962), and later by Pickering and Hilton (1988, their Figure 62), among others.

driven by the vertical variations in the density of the ocean water caused by changes in temperature and salinity. As a consequence, baroclinic currents are commonly associated with internal waves and internal tides that propagate along boundaries of density stratifications in the deeper part of the ocean (Figure 2). Baroclinic currents can occur in mid-ocean depths and along the ocean floor of continental slopes and submarine canyons. However, baroclinic currents do not occur along the deep abyssal floors (see Section 9.2). Despite its common usage in physical oceanography, the 'baroclinic' concept still remains an unfamiliar theme in process sedimentology.

The shelf edge is the defining bathymetric boundary between the shallow mixed ocean and the deep stratified (baroclinic) ocean (Figure 2). The shelf edge concept is not applicable to gently sloping carbonate ramp setting or to periods of sea-level lowstands.

According to the American Meteorological Society (Ocean Motion, 2012), a pycnocline is the interface between the mixed and the deep ocean layers where the density gradient is the greatest (Figure 2). The density gradient is caused either by differences in temperature (*i.e.*, thermocline) or by salinity (*i.e.*, halocline). The ocean′s uppermost 100 m or so is well mixed by wind-driven surface currents. In general, the deep-marine environment (*i.e.*, > 200 m in bathymetry) is vertically stratified (Figure 2).

2.2 Internal waves and internal tides

Internal waves are gravity waves that oscillate along the interface between two water layers of different densities, known as pycnocline (Figure 2). Although pycnoclines are primary boundaries of density stratification for the existence of internal waves, they are not essential in all cases. This is because any hydrostatically stable density stratification is sufficient for sustaining internal waves (Garrett and Munk, 1979). In order to distinguish these additional boundaries from pycnoclines, the term 'secondary density stratification' was introduced by Shanmugam (2013a) (Figure 2). Density stratification in the water column of modern oceans is routinely recognized on high-resolution seismic profiles (Susanto *et al.*, 2005). But there are no sedimentologic criteria to recognize paleo-pycnoclines in the ancient stratigraphic record. Internal waves are made visible at the sea surface through the effect of internal wave currents on surface roughness (Gargett and Hughes, 1972). Internal waves are common phenomena in coastal seas, open ocean, fjords, lakes, and the atmosphere. Internal tides are internal waves at a tidal frequency (Shepard, 1975).

Internal solitary waves or solitons, consisting of a single isolated wave, are ubiquitous in stratified fluids. Apel

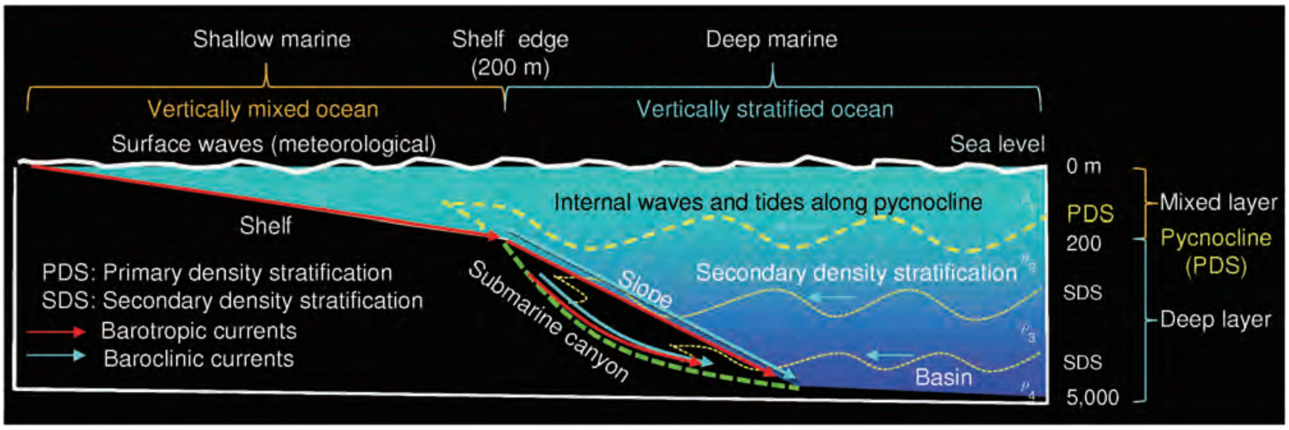

Figure 2 Schematic diagram showing the position of the pycnocline (*i.e.*, primary density stratification), where density gradient is the sharpest, between mixed (upper) and deep (lower) ocean layers of different densities. Internal waves and tides propagate along boundaries of both primary and secondary density stratifications. Note that the shelf edge at 200 m is used as the defining boundary between shallow-marine and deep-marine environments. Meteorological surface waves dominate shallow-marine (shelf) environments, whereas oceanic internal waves and astronomical internal tides propagate along boundaries of density stratification in deep-marine environments. Barotropic currents (red arrow) are generated by surface waves and tides, whereas baroclinic currents (cyan arrow) are generated by internal waves and internal tides. Note that baroclinic currents flow along density stratifications in open water and along the seafloor. Relative increase in density of fluid layer with increasing bathymetry is shown by ρ_1, ρ_2, ρ_3, and ρ_4. Note that pycnoclines intersect only the sloping seafloor topography, but not the near-horizontal basin plain. Diagram is a composite compilation of related concepts. This is partly based on Inman *et al.* (1976), Maxworthy (1979), Shanmugam (2008a), and Ocean Motion (2012). Not to scale. From Shanmugam (2013a), with permission from AAPG.

(2002) defined this class as follows: "*Solitary waves are a class of nonsinusoidal, nonlinear, more or less isolated waves of complex shape, which occur commonly in nature. These waves maintain their coherence, and hence visibility, through nonlinear hydrodynamics and appear as long, quasilinear stripes in imagery*." Internal solitary waves travel in packets. The number of individual oscillations within the packet increases as its age increases, with one new oscillation added per Brunt-Väisälä period. The Brunt-Väisälä frequency or buoyancy frequency (*e.g.*, Apel *et al.*, 2006; their equation 10) is expressed as follows:

$$N(z) = \sqrt{-\frac{g}{p_0}\frac{dp_0}{dz}}$$

Where

g = gravitational acceleration

p_0 = equilibrium fluid density

z = height in fluid

dp_0/dz = change in fluid density with height in fluid.

Apel (2002) summarized the physical properties of internal solitary waves, and Shanmugam (2013a) has updated them. Internal solitary waves commonly exhibit (1) higher wave amplitudes (5−50 m) than surface waves (<2 m), (2) longer wavelengths (0.5−15 km) than surface waves (100 m), (3) longer wave periods (5−50 min) than surface waves (9−10 s), and (4) higher wave speeds (0.5−2 m s^{-1}) than surface waves (25 cm s^{-1}). Maximum speeds of 48 cm s^{-1} for baroclinic currents were measured on guyots. The amplitudes are rank ordered, with the largest at the front of the packet and the smallest at its rear. The wavelengths and the crest lengths are also rank ordered, with the longest waves at the front of the group. Unlike surface waves, internal waves can stretch over tens of kilometers in length. Characteristically, a younger (smaller) wave packet follows an older (larger) packet forming a wave train in the Sulu Sea (Shanmugam, 2013a, his Figure 6). Unlike surface waves, internal waves can propagate not only horizontally, but also vertically and in any direction in between (Cacchione and Pratson, 2004). Although internal tides have large amplitudes in the deep ocean, their sea-surface height manifestations are only of a few centimeters (Ray and Mitchum, 1997). This is caused by the great increase in density difference between air and water at the sea-surface interface in comparison to the density difference between fluids (*i.e.*, water-water) at internal interfaces. For example, the density of water is 1000 times greater than that of air.

2.3 Process sedimentology

Process sedimentology is the founding principle behind all process interpretations of sedimentary rocks (see details in Shanmugam, 2006a, Chapter 1). Basic requirements of this discipline are (1) a knowledge of physics, in particular, soil mechanics and fluid mechanics (Sanders, 1963; Brush, 1965), (2) the routine application of uniformitarianism, (3) objective description of the rock, (4) documentation of excruciating details in sedimentological logs, (5) pragmatic interpretation of processes using sedimentary structures, (6) the absolute exclusion of facies models, and (7) the use of common sense.

The term “tidalite” was originally introduced for alternating units of traction and suspension deposition from shallow-water tidal currents (Klein, 1971). The genetic term “internal tidalites” is appropriate for deposits of internal tidal currents. Deposits of baroclinic currents, associated with both internal waves and internal tides, could be termed “baroclinites” (Shanmugam, 2013a).

3 Evidence for oceanic pycnoclines

The supreme evidence for interpreting internal-wave and internal-tide deposits in the rock record is the physical evidence for oceanic pycnoclines (Shanmugam, 2012a). Without that evidence for density stratification, no difference between a surface tidalite formed by surface (barotropic) tides on a shallow-marine shelf and an internal tidalite formed by internal (baroclinic) tides in a deep-marine slope or canyon environment exists. The interpretations of ancient strata as deposits of internal waves and internal tides by Gao and his colleagues (Gao and Eriksson, 1991; Gao *et al.*, 2013; He *et al.*, 2011) were not based on the ultimate evidence for pycnoclines. Shanmugam (2012a) debated this problem with reference to interpretation of Ordovician deposits in China by He *et al.* (2011). In their reply, He *et al.* (2012) conceded that “*Conclusive evidence for the existence of a pycnocline in our stratigraphic record is currently lacking. Because the absence of proof is not proof of the contrary, it is unreasonable to use this as a basis to negate the possibility that these deposits may have been generated by internal waves and internal tides*.”

4 Distinguishing between internal-wave and internal-tide deposits

Gao *et al.* (2013) treat both internal-wave and internal-tide deposits as one and the same. Internal waves can be distinguished from internal tides in modern oceans by monitoring tidal frequency. However, the distinction between deposits associated with internal waves and those associated with internal tides in the ancient stratigraphic record has never been resolved using core studies of modern analogs. For this reason, He *et al.* (2008, 2011) have combined characteristic structures of both internal-wave and internal-tide deposits together. These sedimentary structures are (1) bidirectional cross-lamination, (2) cross-lamination dipping upslope, (3) multidirectional cross-lamination, (4) flaser bedding, (5) wavy bedding, (6) lenticular bedding, (7) double mud layers, and (8) reactivation surfaces. The problem is that these sedimentary structures are associated with deposits of tidal currents not only in shallow-marine environments (Reineck and Wunderlich, 1968; Klein, 1970; Visser, 1980; Terwindt, 1981; Allen, 1982; Nio and Yang, 1991; Dalrymple, 1992; Alexander *et al.*, 1998; Archer, 1998; Shanmugam *et al.*, 2000; Davis and Dalrymple, 2012) but also in deep-marine environments (Klein, 1975; Cowan *et al.*, 1998; Shanmugam, 2003; Shanmugam *et al.* 2009; Mutti and Carminatti, 2012). This is an important area of future sedimentological research.

5 Bidirectional cross-bedding

The review by Gao *et al.* (2013) is symptomatic of research with chronic problems dealing with deposits of internal waves and internal tides, which include the first facies model of an Ordovician internal-tide deposit from the central Appalachians (Figure 1, location A). For the first time, bidirectional cross-bedding was related to internal-tide origin in submarine channels and canyons in the Appalachian study (Gao and Eriksson, 1991). However, bidirectional current directions of baroclinic currents associated with modern internal waves and internal tides are still murky.

Gao *et al.* (2013) claim that “*The most typical sedimentary structures of internal-wave and internal-tide deposits are bidirectional cross beds* (*Figures* 2, 3) *and unidirectional cross-beds with laminae dipping up the submarine canyon or regional slope*…” This claim is based strictly from their study of ancient stratigraphic record, without any validation from modern analogs. Although Shepard *et al.* (1979) documented along-canyon bidirectional tidal currents in submarine canyons, it is unclear as to whether these currents are barotropic or baroclinic in origin (Shanmugam, 2013a, 2013b).

There are four major types of submarine canyons based on the position of canyon heads, the role of surface (barotropic) tide, the role of internal (baroclinic) tide, *etc.* (Figure 3), which should be taken into account when interpret-

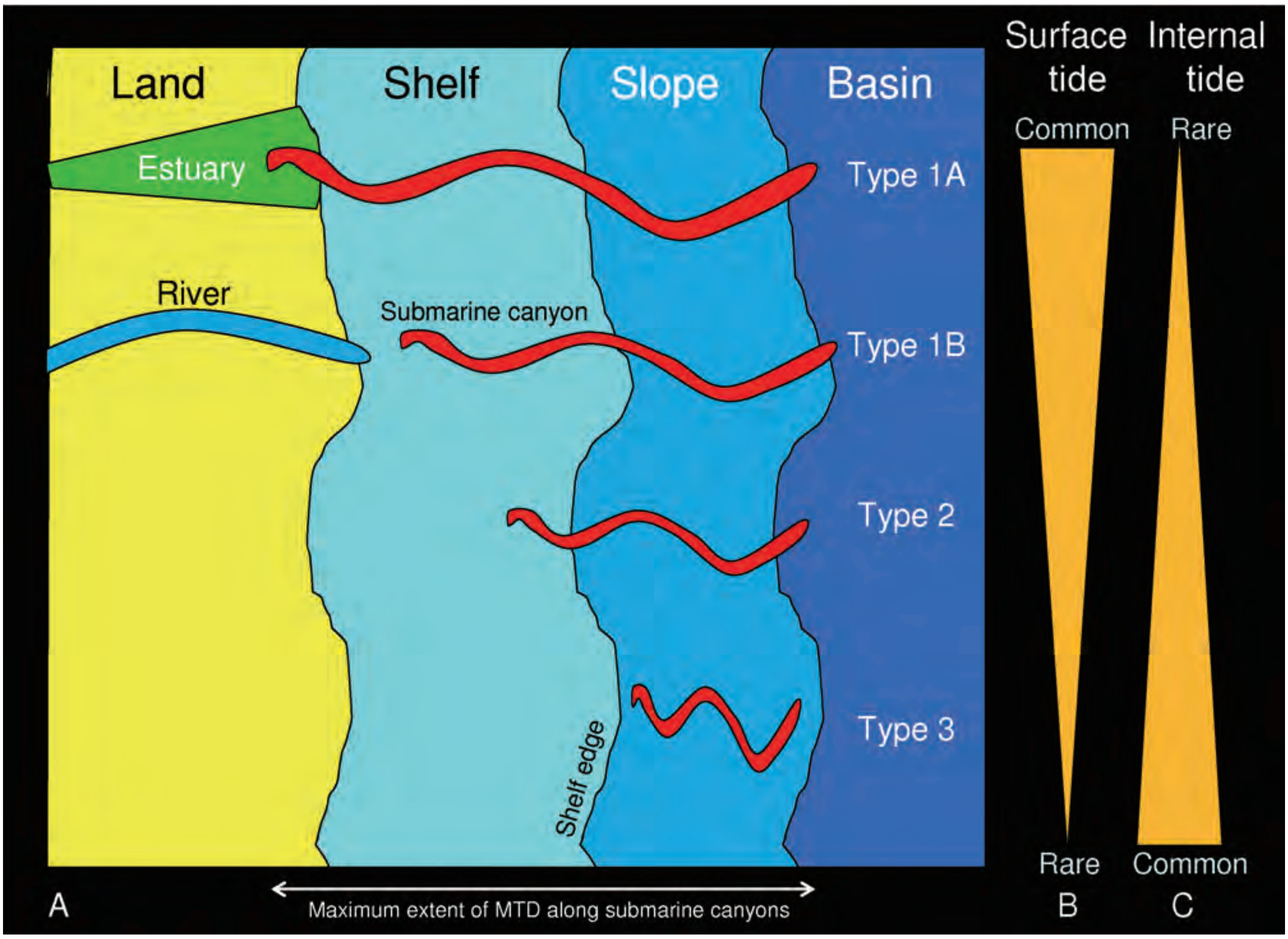

Figure 3 A−A classification of submarine canyons with four basic types. (1) Type1A: land-incising canyon into estuary or river system with tidal influence. (2) Type 1B: shelf-incising canyons having heads with connection to a major river or estuarine system, but they do not incise onto the land. (3) Type 2: shelf-incising canyons with no clear connection to a major river or estuarine system. (4) Type 3: slope-incising blind canyons with their heads confined to the continental slope. The distribution of mass-transport deposits (MTD) in submarine canyons is controlled by the extent of the canyons (arrow); B−Increasing influence of surface (barotropic) tides from Type 3 to Type 1A canyons; C−Increasing influence of internal (baroclinic) tides from Type 1A to Type 3 canyons. The classification of submarine canyons into three types using position of canyon heads was proposed by Harris and Whiteway (2011). Diagram was conceived by Shanmugam (2012b) with information on surface and internal tides, published with permission from Elsevier.

ing ancient rock record.

Unlike barotropic tidal currents that flow along the axis of the canyon, baroclinic currents flow across the canyon and in a direction parallel to the shelf break (Allen and Durrieu de Madron, 2009). Selected examples of cross-canyon currents are: (1) Hydrographer Canyon, U.S. Atlantic (Wunsch and Webb, 1979); (2) Monterey Canyon, U.S. Pacific (Kunze *et al*., 2002); and (3) Gaoping Canyon, Taiwan (Lee *et al*., 2009). In such canyons, baroclinic currents cannot generate bidirectional cross-bedding.

Importantly, the development of bidirectional cross-bedding in modern submarine canyons or channels by internal waves or internal tides has never been documented using sediment core. In the modern Gulf of Cadiz (Figure 1, location B), where internal waves and internal tides are active today (Alvarado-Bustos, 2011; Sanchez-Garrido *et al.*, 2011; Quaresma and Pichon, 2013), Stow *et al.* (2013) reported current reversal associated with internal tidal currents in the modern Cadiz Channel, but they did not report bidirectional cross-bedding in the core. Therefore, the presumed genetic link between bidirectional cross-bedding and internal tidal currents has not yet been established using modern analogs.

Satellite images of modern internal waves reveal that the directions of propagation of internal waves are highly variable with respect to the shoreline, the shelf edge, and the channel axis (Figure 4). Selected examples are: (1) internal waves that propagate towards the shoreline,

(2) internal waves that propagate away from the shoreline or the shelf edge, (3) internal waves that propagate nearly parallel to the shoreline, (4) internal waves that propagate in the direction parallel to the strait axis or channel axis, controlled by a sill, (5) internal waves that propagate in the same direction on both sides of a strait, controlled by a sill, and (6) two wave trains of internal waves propagating in opposite directions from the point of origin, a sill, in a strait (Figure 4). But there is no systematic linking of wave-propagation directions seen as the sea-surface manifestations on satellite images with their respective influence on internal sedimentary structures (*i.e.*, dip directions) in the depositional bedforms on the modern seafloor. This lack of a link between the direction of wave propagation along pycnoclines and the direction of current movement on the seafloor is further compounded by the presence of local

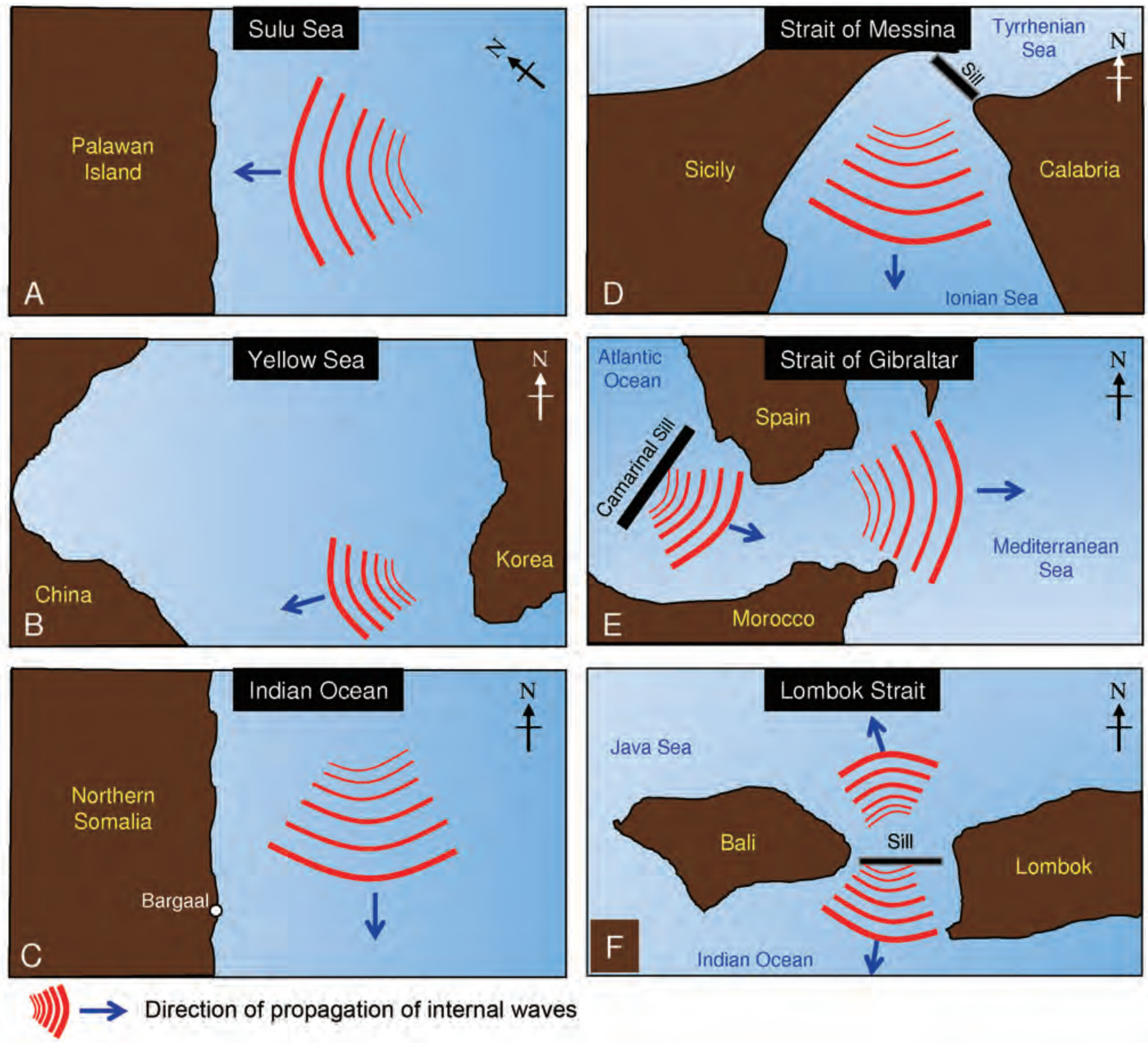

Figure 4 Maps showing variable directions of propagation of internal waves with respect to shoreline or shelf edge seen as surface manifestations on satellite images. A−Internal waves propagating towards the shoreline of Palawan Island in the Sulu Sea (Shanmugam, 2013a, his Figure 6); B−Internal waves propagating away from the shoreline or shelf edge in the Yellow Sea; C−Internal waves propagating nearly parallel to the shoreline of northern Somalia in the Indian Ocean; D−Internal waves propagating parallel to the strait or channel axis in the Strait of Messina; E−Internal waves propagating in the same direction on both sides of the Strait of Gibraltar. Note position of the Camarinal Sill at the point of origin of internal waves; F−Internal waves propagating in opposite directions from the point of origin, which is a sill in the Lombok Strait (Susanto *et al*., 2005). Features shown are schematic and not to scale. From Shanmugam (2013a), with permission from AAPG.

sills on the seafloor that invariably control the direction of wave propagation (Figure 4D, 4E, and 4F). Furthermore, Dykstra (2012, his Figure 14.3b caption) state that "*If more than one wave is present in the ocean at different depths, which can occur in well-stratified water with significant seafloor topography* (*e.g.* *Robertson*, 2005), *current directions along the seafloor can become quite complicated*." Under this umbrella of knowledge vacuum on current directions, the use of bidirectional cross-bedding as evidence for deposition by baroclinic currents in outcrop studies is sedimentologically erroneous.

6 Traction structures

Gao *et al.* (2013, their Table 1) and Gao *et al.* (1998) claim that various traction structures (*e.g.*, unidirectional cross-bedding, cross-laminated lenses, *etc.*) are evidence of internal waves. This claim is false because traction structures have been documented to form by other deep-water processes (Shanmugam, 2012b). There are four types of deep-water bottom currents, namely (1) thermohaline-induced geostrophic bottom currents (*i.e.*, contour currents), (2) wind-driven bottom currents, (3) deep-marine tidal bottom currents, and (4) baroclinic currents, are considered (Shanmugam, 2008a). All four types of bottom currents can develop traction structures (Figure 5). For example:

Traction structures are considered to be an integral part of contourites (*i.e.*, deposits of contour currents) (Hubert, 1964; Hollister, 1967; Hsü, 1989; Mutti, 1992; Mutti and Carminatti, 2012; Ito, 2002; Martın-Chivelet, *et al.*. 2008; Shanmugam, 2000, 2008a).

In the Ewing Bank 826 area of the Gulf of Mexico, tractions structures in the Plio-Pleistocene intervals have been interpreted to be by the wind-driven Loop Current (Shanmugam *et al.*, 1993a, 1993b) (Table 1). These deposits are characterized by cross-bedding, ripple lamination, and horizontal lamination (Figure 5).

In the Krishna-Godavari Basin in the Bay of Bengal, traction structures in the Pliocene sandy intervals have been related to deep-marine tidal currents (Shanmugam *et al.*, 2009).

On the Horizon Guyot in the Pacific Ocean, traction bedforms have been attributed to reworking by internal tidal currents (Lonsdale *et al.*, 1972). These are baroclinic sands.

The presence of traction structures in cores and outcrops have long been recognized as evidence for bottom-current reworked sands in deep-water strata (Hsü, 1964, 2008; Hubert, 1964; Klein, 1966; Hollister, 1967; Natland, 1967; Piper and Brisco, 1975; Shanmugam *et al.*, 1993a, 1993b; Shanmugam, 2008a; Martın-Chivelet *et al.*, 2008; Mutti and Carminatti, 2011). Hsü (1964) argued that traction structures in deep-marine sands were more meaningful as deposits of bottom currents than of turbidity currents. Traction structures are common in deep-water petroleum reservoirs worldwide (Table 1). The challenge is how to distinguish parallel laminae formed by contour currents from those formed by wind-driven bottom currents in the ancient stratigraphic record.

Gao *et al.* (2013) state, "*The grain−size of sandstone* (*grainstone*) *of internal-tide and internal-wave deposit origin is similar to that of fine−grained turbidites and sandy contourites*. *Distinguishing correctly internal-tide and internal-wave deposits, turbidites and contourites is also the key to recognizing internal-tide and internal-wave deposits*. *There are distinctions between them in terms of sedimentary structures*, *relationships between the direction of directional sedimentary structures and palaeogeographical patterns*, *vertical successions*, *bioturbation*, *and so on*." However, distinguishing contourites from other deep-water deposits is impractical (Shanmugam, 2012b).

Stow *et al.* (2013) have interpreted sands and gravels as "sandy contourites" in the Gulf of Cadiz (Figure 1, location B). Although this site served as the birthplace for the first contourite facies model (Faugères *et al.*, 1984), the Gulf of Cadiz is an extremely complex deep-water environment with multiple interactive processes (*e.g.*, Mediterranean Outflow Water (MOW), internal waves, internal tides, *etc.*) and with intricate submarine channels, ridges, and sills. For these reasons, there are no objective criteria to distinguish traction structures formed by contour currents from those formed by internal waves or internal tides. Bioturbation is not unique to contourites (Shanmugam, 2012b, 2013a). Therefore, there are no objective criteria to distinguish contourites from baroclinic sands.

Furthermore, there are process-sedimentological challenges in distinguishing tsunami-related deep-water deposits with traction structures from other deposits (Shanmugam, 2006a, 2006b, 2012c). By ignoring this wealth of published information on traction structures associated with various bottom currents, Gao *et al.* (2013) promote a falsehood on the link between traction structures and internal waves, without a critical analysis.

7 Vertical facies models

Gao *et al.* (2013) state that "*Four basic sedimentary successions of internal-wave and internal-tide deposits are*

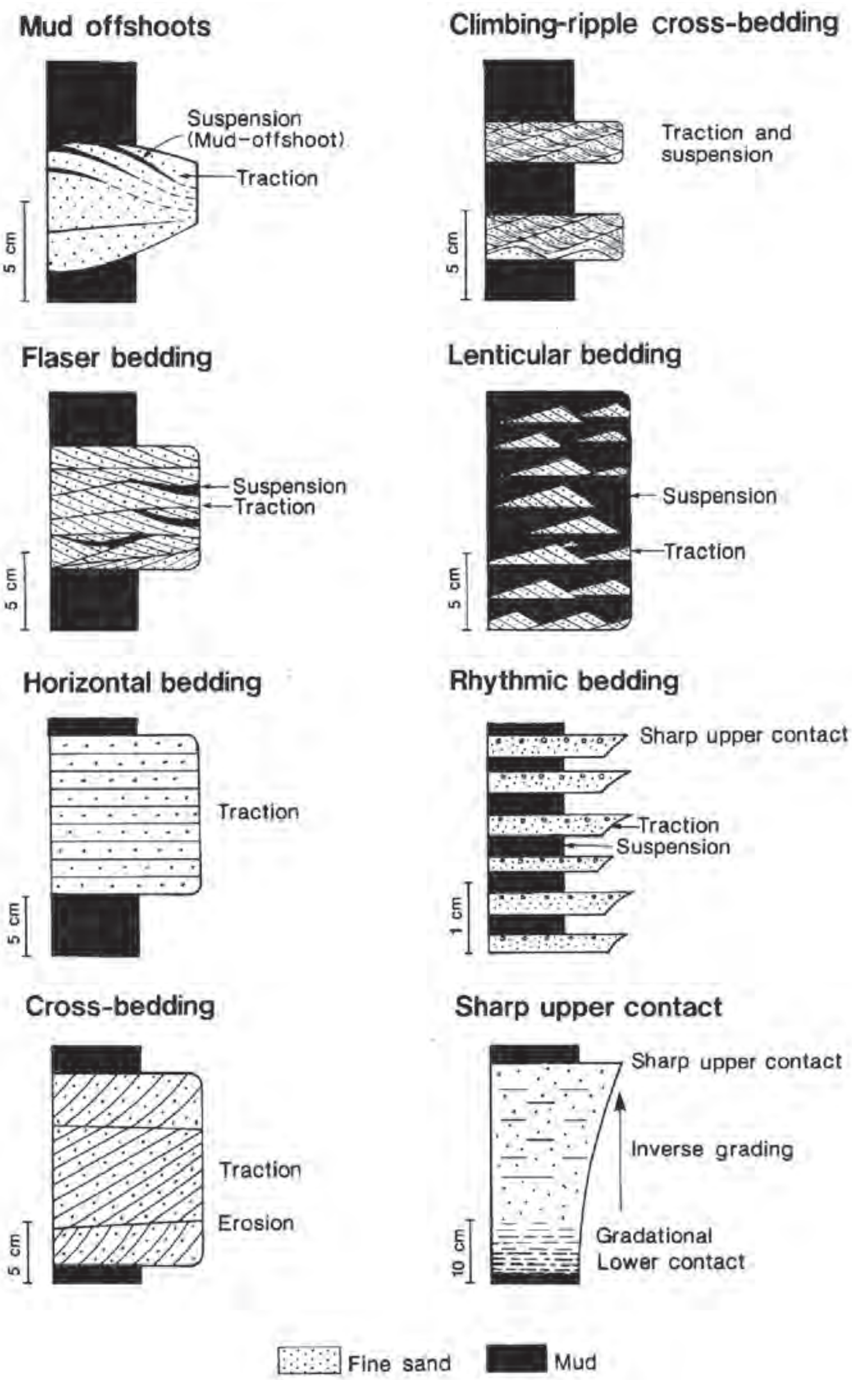

Figure 5 Summary of traction features interpreted as indicative of deep-water bottom-current reworking. From Shanmugam *et al.*, 1993a, with permission from AAPG.

recognized, which include: (1) *a coarsening-up and then fining-up succession* (*bidirectional graded succession*), (2) *a fining-up succession* (*unidirectional graded succession*), (3) *a coarsening-up and then fining-up succession with couplets of sandstone and mudstone* (*bidirectional graded couplet succession*), *and* (4) *a mudstone-oolitic limestone-mudstone succession* (*Figure* 4.)" These trends are strictly from study of outcrops in China and the central Appalachians (USA). I have provided detailed critiques of these models elsewhere (Shanmugam, 2012a, 2013a, 2013b). There are fundamental questions that still remain to be addressed.

1) Why the four vertical trends are considered indicative of deposits of internal waves and internal tides?

2) Are there modern analogs to support these vertical trends?

3) Are there theoretical solutions that can explain these vertical trends?

4) Are there laboratory experimental works that can replicate these vertical trends?

5) Are there differences in vertical trends between internal-wave and internal-tide deposits?

6) What is so unique about the lithofacies “a mudstone-oolitic limestone-mudstone succession” (their Figure 4f) that implies deposition from internal waves or internal tides?

7) What are the criteria to distinguish deposits of barotropic tidal currents in shallow-marine environments from those of baroclinic tidal currents in deep-marine environments?

8) What is so unique about the upward-coarsening trend with bidirectional cross-bedding (their Figure 4a)? For example, upward-coarsening trends with bidirectional cross-bedding have been documented in estuarine tidal sand bars (Shanmugam *et al.*, 2000, their Figure 9). Upward-coarsening trends are also considered typical of storm deposits (Bádenas and Aurell, 2001; Pomar *et al.*, 2012).

9) The uncertainty of outcrop-based vertical facies models has long been recognized for storm (Dott and Bougeois, 1982), fluvial (Miall, 1985) and turbidite (Shanmugam *et al.*, 1985) deposits. What is the reason for ignoring this tumultuous sedimentological history behind vertical facies models?

He *et al.* (2011, their Figure 11) proposed an idealized vertical facies model that closely mimics the Ta, Tc, and Te divisions of the turbidite facies model, known as the ‘Bouma Sequence’ (see Shanmugam, 2013a, his Figure 15D). Even the classic ‘Bouma Sequence’ (Bouma, 1962) is considered obsolete due to lack of theoretical, experimental, and empirical basis (Hsü, 1964, 1989, 2004, 2008; Sanders, 1965; Van der Lingen, 1969; Leclair and Arnott, 2005; Shanmugam, 1997a, 2000, 2002, 2006a, 2012b, 2013e). In spite of these controversies, what is the reason for adopting the ‘Bouma Sequence’ in the study by He *et al.* (2011)?

Given the fact that the very existence of sandy and gravelly turbidity currents has never been documented in modern oceans, the outcrop-based turbidite facies models (Bouma, 1962; Lowe, 1982) and their more recent versions (Talling *et al.*, 2012, their Figure 3) and explanations (Postma *et al*., 2014) are irrelevant for interpreting ancient rock record objectively worldwide (Shanmugam, 2014). The turbidite facies models, which are nothing more than a groupthink, have suppressed scientific curiosity during the past 50 years by averting novel observations and by preventing innovative interpretations. Analogous to turbidite facies models, facies models proposed for deposits of internal waves and internal tides will impose similar limitations due to a lack of scientific foundation.

8 Sea-level changes

Gao *et al.* (2013) claim that “*With a rise in sea level, the distance from sediment source areas to depositional areas gradually increases, coarse-grained clasts are stranded closer to source areas, and internal waves and internal tides become dominant in reworking fine-grained gravity–flow deposits.*” In order to evaluate the validity of this claim, one needs to evaluate the origin of internal waves and internal tides.

Internal waves are triggered by natural forces like (a) wind (meteorological force), (b) tide (astronomical force), (c) tropical cyclones (Nam *et al.*, 2007), (d) tsunamis (Santek and Winguth, 2007), (e) river plumes (Nash and Moum, 2005), and by man-made activities like sailing ships (Apel and Gjessing, 1989). Tropical cyclones also influenced the generation of internal tides (Davidson and Holloway, 2003). The problem is that these triggering mechanisms are not unique to a period of rise in sea level.

Empirical data on tropical cyclones (meteorological phenomena) and tsunamis (oceanographic phenomena) from the Indian, Atlantic, and Pacific Oceans reveal that they are common events today (Shanmugam, 2008b). Because tsunamis are most commonly triggered by earthquakes (*e.g.*, 2004 Indian Ocean Tsunami triggered by the Sumatra-Andaman Earthquake), no relationship can exist between sea level changes and the timing of tsunamis (Shanmugam, 2007, 2008b). In other words, tsunami-triggered internal waves can occur irrespective of sea-level changes.

Short-term events, such as earthquake-triggered tsunamis, last only for several hours or days. On the other hand, long-term events, such as sea-level changes, last for thousands to millions of years (Shanmugam, 2012b, 2012c, 2014). Therefore, numerous short-term tsunamis can occur during a single long-term rise in sea level. But there are no criteria to distinguish internal-wave deposits associated with earthquake-induced tsunamis in the stratigraphic record.

In short, a rise in sea level is irrelevant to understanding internal-wave sedimentation in deep-water environments.

9 International literatures

The purpose of this section is to demonstrate that Gao *et* *al.* (2013) tend to evade relevant international literatures in their review. I also use this section to illustrate sedimentological challenges that still exist in distinguishing types of bottom-current reworked sands in the ancient sedimentary record.

9.1 Stratified oceans

In a comprehensive review of deep-water bottom currents and their deposits, Shanmugam (2008a) observed that "*Gao et al*. (1998) *interpreted ancient strata with bidirectional cross-bedding*, *flaser bedding*, *wavy bedding, and lenticular bedding as deposits of internal tides based on associated deep-water turbidite and slump facies*. *The key to interpreting deposits of* '*internal tides*' *or baroclinic currents in the rock record is the vidence for tidal currents in a stratified deep ocean*. *Without that evidence for density stratification*, *there is no difference between a tidal deposit formed by surface* (*barotropic*) *tide in a shallow-marine shelf and a tidal deposit formed by internal* (*baroclinic*) *tide in a deep-marine slope or canyon environment*." Howver, Gao *et al.* (2013) have failed to acknowledge this basic weakness in their interpretation. If they disagree with the above assessment, then they need to refute the appraisal with counter reasoning and field data.

9.2 Seafloor topography

Gao Zhenzhong, as a co-author of He *et al.* (2011), proposed an abyssal-basin palaeogeography, characterized by internal-tide and internal-wave deposits, for the the Middle Ordovician Xujiajuan Formation of the Xiangshan Group, Ningxia, China (Figure 1, location D). Such interpretations totally ignore relevant publications on the role of seafloor topography in generating internal waves. For example, Polzin *et al.* (1997) have documented that the turbulent mixing of internal waves is concentrated over the rough seafloor topography of the Mid-Atlantic Ridge in the Brazil Basin, South Atlantic Ocean. Using the cross-isopycnal data from the Brazil Basin (see Polzin *et al.*, 1997, their Figure 2), Jayne *et al.* (2004) have illustrated the concept of turbulent mixing in the Brazil Basin. Clearly, ubiquitous internal waves are generated over the mid-ocean ridge by the tides flowing over rough topography, whereas internal waves are conspicuously absent over the smooth abyssal floor (St. Laurent *et al.* (2012, their Figure 1; Turnewitsch *et al.*, 2013) (see also Figure 6). Empirical data also show that internal waves and internal tides are common over submarine guyots in the Pacific Ocean (Lonsdale *et al.*, 1972), but absent or insignificant over the flat abyssal floor (Figure 6). He *et al.* (2011) did not provide any evidence of submarine guyots or seamounts surrounded by abyssal-basin palaeogeography during the Middle Ordovician in explaining internal-wave deposits. Shanmugam (2012a) pointed out this shortcoming in their paper (He *et al.*, 2011), which has become a source of lively debate in *Geo-Marine Letters* (Shanmugam, 2012a; He *et al.*, 2012). Surprisingly, Gao *et al.* (2013) did not cite the discussion and reply in their review. Nor did they explain the origin of internal waves and internal tides over the flat abyssal floors in the Middle Ordovician of the Xiangshan Group, Ningxia, China.

9.3 High-velocity currents

There are other relevant articles on physical oceanography and process sedimentology (*e.g.*, Dykstra, 2012; Mulder *et al.*, 2012; Pomar *et al.*, 2012), which Gao *et al.* (2013) did not cite. For example, Mulder *et al.* (2012) believed that high-velocity currents in submarine canyons in the modern Bay of Biscay were related to internal tides, but did not provide empirical data in distinguishing baroclinic currents from barotropic currents.

9.4 Hummocky cross-stratification

In explaining the origin of hummocky cross-stratification (HCS), He *et al.* (2011 with Gao as a co-author) state, "*It probably represents the product of combined flows generated by the interaction of short-period internal waves with turbidity currents*." Although the origin of HCS has been controversial (Shanmugam, 2013a, 2013b), Gao *et al.* (2013) totally ignored the controversies. For example, Harms *et al.* (1975) first proposed that HCS was a product of storm deposition. However, Morsilli and Pomar (2012) attributed the origin of HCS to internal waves. Following this trend, Pomar *et al.* (2012) reinterpreted the Upper Jurassic "storm" strata, exposed near Ricla in NE Spain (Figure 1, location C) with hummocky cross-stratification (HCS), as 'internal-wave deposits'. Their reinterpretation implies that associated HCS in these strata was also formed by internal waves. Pomar *et al.* (2013) did not justify the origin of HCS by internal waves with supporting data and convincing explanation on mechanics of deposition.

9.5 Modern analogs

In developing facies models for ancient internal-wave and internal-tide deposits, Gao *et al.* (2013) need to evaluate published empirical data on modern internal waves and internal tides. For example, Saller *et al.* (2006) interpreted petroleum-producing Miocene sands with parallel and cross laminae as turbidites using the turbidite facies

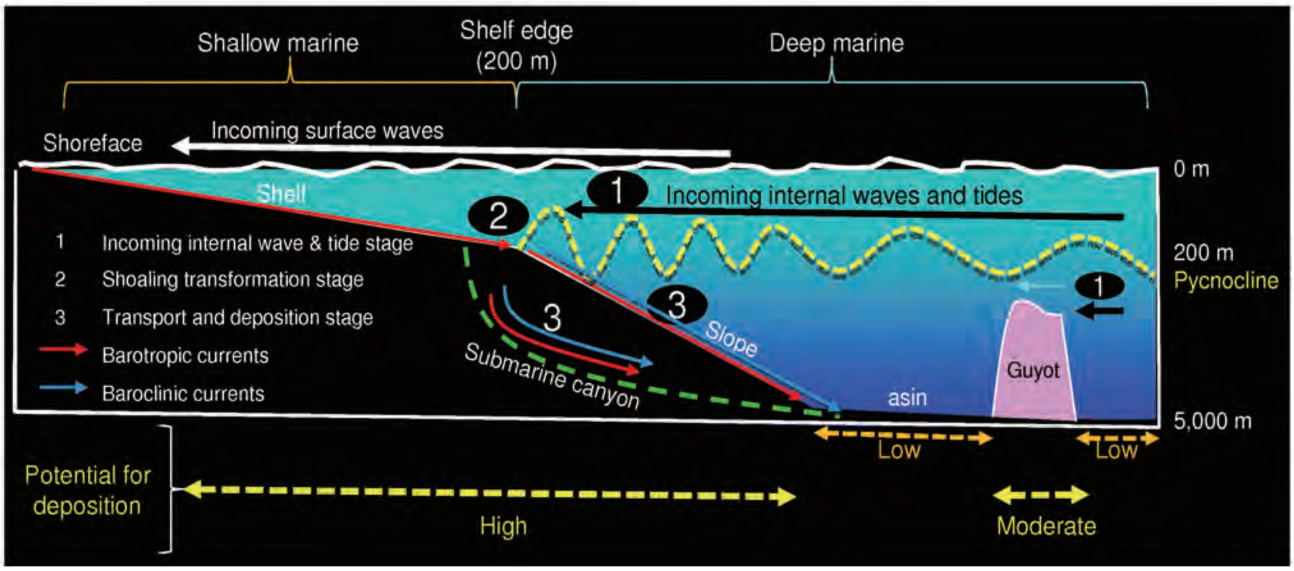

Figure 6 A conceptual oceanographic and sedimentologic framework showing deposition from baroclinic currents on continental slopes, in submarine canyons, and on guyots. On continental slopes and in submarine canyons, deposition occurs in three progressive stages: (1) incoming internal wave and tide stage, (2) shoaling transformation stage, and (3) sediment transport and deposition stage. Continental slopes and submarine canyons are considered to be environments with high potential for deposition from baroclinic currents. In the open ocean, baroclinic currents can rework sediments on flat tops of towering guyot terraces, without the need for three stages required for deposition on continental slopes. In this model, basin plains are considered unsuitable environments for deposition of baroclinic sands. Not to scale. From Shanmugam (2013a), published with permission from AAPG.

model of Bouma (1962) in the Kutei Basin (Figure 1, location E). The problem here is that Saller *et al.* (2006) have overlooked the existence of empirical data on bottom currents associated with various modern oceanographic phenomena in the Makassar Strait (Figure 1, location E). They are (1) documented Indonesian throughflow (Gordon, 2005), (2) observed internal waves (Hatayama, 2004), (3) observed internal tides (Ray *et al.*, 2005), and (4) measured velocities of deep tidal currents (Nummedal and Teas, 2001; Wajsowicz *et al.*, 2003). These data are relevant in interpreting Miocene sands alternatively as deep-marine tidalites or baroclinic sands (Shanmugam, 2008c, 2014).

9.6 Seismic wave geometry

In discussing large-scale seismic geometry, Gao *et al.* (2013) state that "…*interpreting some deep-sea large-scale sediment waves as having an internal-wave origin*…" Sediment waves associated with internal waves and internal tides are poorly understood from a process sedimentology viewpoint (Shanmugam, 2012b). At present, no objective criteria exist for distinguishing wave geometry created by internal tidal currents from wave geometry created by contour currents (Nielson *et al.*, 2008) or by turbidity currents (Normark *et al.*, 1980) using seismic profiles alone (Shanmugam, 2013a). This field remains an important area of future research.

10 Concluding remarks

Empirical data on the physical characteristics of modern internal waves and internal tides from 51 regions of the oceans of the world, descriptions of core and outcrop worldwide carried out by the author, and selected case studies published by other researchers have resulted in the following key conclusions:

Core-based sedimentologic studies of modern sediments emplaced by baroclinic currents on continental slopes, in submarine canyons, and on submarine guyots are totally lacking.

No cogent sedimentologic or seismic criteria exist for interpreting ancient strata as of internal-wave and internal-tide deposits in outcrops or cores.

Outcrop-based vertical facies models proposed for ancient deposits are untenable due to an absolute lack of theoretical, experimental, and empirical foundation. At this embryonic stage of our understanding of internal waves and internal tides in terms of their depositional characteristics, the promotion of vertical facies models with lingering questions (see Section 7) is like putting the cart before the horse!

Real potential exists for misinterpreting deep-marine baroclinic sands as turbidites, contourites, tsunami-related deposits, *etc.*

The interpretation of ancient strata by Gao and his colleagues were made without validation from modern analogs (*i.e.*, without uniformitarianism).

In light of these conclusions, it would be helpful, if Gao *et al.* could respond to the issues raised in this discussion and could explain the basis for their interpretation.

In future research, it is imperative to select appropriate modern deep-marine settings for understanding the link between baroclinic currents and their deposits. At such settings, field research must be carried out by obtaining physical measurements of currents and by documenting disposition of sedimentary structures in long sediment cores. It is also necessary to conduct laboratory experiments for understanding depositional mechanics of sedimentary structures formed by baroclinic currents. Such a coordinated approach is likely to yield the much-needed clarity.

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